

VAPOR CORE PROPULSION REACTORS

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Figure 1 describes INSPI's charter, participating institutions and projects. Essentially we have been in existence for five years and we have been funded to work on advanced nuclear space power reactors, including gas cores. A significant amount of work has been done recently.

Earlier research used small amounts of UF₆, flowing it in argon. We did critical experiments at 20 kilowatts. One time we went to a hundred kilowatts for a few seconds, got there and came down. Most of the fuel was in the cavity, about 4 kilograms of uranium hexafluoride. We still had solid fuel elements, but we did have a critical system with a significant amount of UF-6 in it. A lot of testing was done on it -- both steady state and dynamic testing. We looked at the characteristics of the system and we validated many of our codes.

Initially, we were having as many as four groups doing different gas core analysis, and eventually a decision was made to focus research on just one concept.

Many research issues were addressed (Figure 2). For example, it became obvious that uranium tetrafluoride is a most preferred fuel over uranium hexafluoride. Every time we start with uranium hexafluoride and go to even lower temperatures (700 K), we end up with uranium tetrafluoride. So why fight mother nature? UF-4 doesn't have the problems UF-6 has, and it has a very attractive vaporization point; 1 atmosphere at 1800 degrees Kelvin. So it is a temperature that's not enormously high, yet hot enough.

We also looked at materials compatible with uranium tetrafluoride, like tungsten, molybdenum, rhenium, carbon. We find that in the molten state, UF-4 and uranium attacked most everything, but in the vapor state they are not that bad. A lot of materials contained them in the vapor state. We identified compatible materials for both the liquid and vapor states.

We actually established a series of analyses to determine how the cavity should be designed. For example, unless your central fuel region is as large as 0.85 of the cavity, the system could be inherently unstable.

We did a series of experiments to determine the properties of the fluid, including enhancements of the electrical conductivity of the system. We now have CFD's and experimental programs that deal with most of the major issues.

We also said that if we do not do nuclear testing from the beginning, eventually we would going to lose our credibility. We performed some small, controlled nuclear testing that gives the gas core credibility.

The beauty of the gas core is that nuclear experiments are easily done. They are rapidly assembled. That is one of their advantages. You can make a gas core with an aluminum tank and a barrel of UF-6. We can design and build and put a gas core in operation in three months.

The only issue is safeguards. Do you have access to the kilograms of uranium that you need?

When working on solid cores, the problem comes down to the fuel. And it will always be like that because as long as you have solid fuel, you are limited (Figure 3).

We nuclear engineers should be using radiation. We stopped using radiation to use heat. That's the way we were trained, that's what we learned. We can use radiation because the vapor cores have an unlimited fuel temperature (Figure 4). They have inherent hot spot equalizers, tremendously high burnup. Limitations are established by the wall cooling, not by the temperature of the heat you can transfer.

The things that are no longer available to you with the solid cores, become the heart and the furnace of your system. You can do all of the things better with vapor cores.

NERVA, which is the standard, is a solid fuel reactor. It might be the only one that we will be able to put out there. My point with this technology is that regardless of how we go, the high temperature technology needs to be developed. It should be done in steps, not jumping to an enormously high temperatures, because temperature costs money and takes time.

What would be the best gas core reactor? Vapor core reactor (Figure 5). Well, it's very simple. The best gas core reactor is one in which the fuel is as hot as you can get it and the fuel is separated from the propellant. The fuel is confined, the propellant goes out and that would be great. So that dream of these two wonderful substances, one fissioning, depositing the energy, and the other coming out -- they cannot coexist unless you want to have really significant separation.

The second best gas core will be one in which you have intimate mixing of the fuel and the propellant, and then you can separate it by some means that might include more than just a vortex flow. You might include some mechanical means of separation.

I am going to initiate the technical part of my talk by looking at what can be done with gas cores and what they are.

We have heard of gas core concepts in which the temperature of the fuel is very, very high, and the mode of heat transfer is preferably by radiation heat transfer. So, you need extremely high heat transfer rates. Then you need a series of complicated yet potentially achievable containment techniques. But, because it is radiative heat transfer, you have to work at very, very high temperatures, and that creates a significant problem as far as how soon we can get this.

There is a second region in which the fuel and the propellant are mixed. The mixture uses some of the best things of the gas cores; the intimate contact, direct molecular collision using direct fission deposition and everything else. Here you have to separate the uranium because the cost of the uranium would be prohibitive, if not economically, then politically.

At less than 5000 degrees Kelvin, there is a region that is of enormous interest to the development of the gas core. That is a region in which the gas core is completely separated from the propellant by a physical wall. The minute you do that you reduce the potential of the gas core. You are now almost a solid core, but not quite. What this allows you to do is to get rid of the limitations of solid cores (Figure 6).

Here you start with a vapor fuel. It has the capacity to occupy different geometrical shapes. The vapor core is a better fuel than standard fuel elements because temperature is no longer limited. Heat transfer is limited by conductance only.

The minute you use a physical barrier, you are severely limiting the heat transfer area. We can use all of the energy transfer mechanisms: direct molecular conduction, fission fragment energy deposition, molecular collision, and radiative heat transfer. Again, the area and the mode of heat transfer are very, very important considerations.

The fundamental features of the vapor reactor (Figure 7) include the fact that energy conversion is not limited by fuel temperature, but rather by wall cooling. The core fission power density is not limited by fuel thermal-mechanical or thermal-hydraulic considerations. There are no geometric constraints on the fuel configuration. If we want to trap it a little bit inside the wall, there are no limitations on the lifetime of the reactor due to the fuel. It also has a much higher burn up because you can burn not only the outside of a fuel element, but you can actually burn the entire load. The gas core has the capability of doing direct ionization, so we can improve the optical and electrical properties of the gas.

We have talked about the advantages of the design features (Figure 8); high fuel utilization, no fuel fabrication, simplified fuel management. There is also inherent hot spot compensation, which means that if you have a hot spot, as fission increases, it gets hot, and it moves into another region. It's a very interesting effect. Density decreases with temperature, which will decrease power in that region. Moving on then, fission product removal is possible.

There is inherent stability in the fuel. The fuel core geometry constraints are minimized. Fuel density can be varied and you can have different power densities in different regions by separation.

Disadvantages include confinement, containment, and recirculation of fuel. Fuel recirculation loops create new problems. One of the main reasons for having a solid fuel is to keep the radioactivity in the fuel. With circulated fuel we have an added problem.

Figure 9 is going to be very familiar to you all. We just took the NERVA core and decided we were going to do a few things to it. What we did is create a cell with a hydrogen core. We put in a graphite wall made of carbon-carbon. Reactivity dropped effectively from 1.4 to 1.07. It really took a beating, but it's still critical. So the cell is arranged with hydrogen, carbon-carbon wall, moderation, uranium tetrafluoride and helium. UF-4 is a poor heat conductor. We added helium to improve heat transfer.

This is a very simple design. Instead of the fuel being dispersed through the matrix, it is now a vapor. But it basically uses all of the NERVA technology.

We do have some significant changes. We put a beryllium reflector on the top because we needed reactivity. We put a graphite reflector on the bottom. This does make the system heavy. Now we could probably do away with those two things if we put 25 centimeters of NERVA fuel in here at the very top. In our calculations, the system K effective increased to about 1.7, and we generated almost two-thirds of the power in here. Why would you do that? Because the solid core has that high power density.

To summarize, Figure 10 shows baseline system parameters for two systems, one is the NVR, which we could call a super NERVA. The other is a generic Vortex Confined Vapor Reactor (VCVR), which is sketched out in Figure 11 (and was discussed by S. Anghaie).

As far as technology readiness is concerned, practically everything is a 2 or 3, except for fuel confinement with internal heat generation (Figure 12). That's not been done at all. We have now capabilities to do research both with very high temperature and nuclear and nonnuclear testing in lab prototypes. Figure 13 and 14 list tasks that should be preformed to rapidly come up to a level in which we can determine what the options are.

Figure 15 lists critical test requirements and safety issues. Many things have been done in the previous five years that actually impact the cost and schedule. We have the fluid dynamics, the high temperature cross sections, and the capabilities of doing experiments at very high temperatures (up to 10000 degrees Kelvin). We also have the facilities.

I think it's critical to get this concept going.

Figure 16 shows research and development costs. It's not a very expensive thing. However, the numbers do not include facilities, so whenever you have to use a facility, you have to add the cost in. I don't know what the facility costs are. They keep changing all the time. So you could easily add \$100 million to this for facilities, and once you start doing your prototype you might have to add \$200 million to it.

I terminate this at ten years. Beyond this point the gas core and solid core cost the same. The reason is that in the first ten years we don't have to have fuel fabricated, tested and qualified. We can have fuel tomorrow.

UF-4 is a nice substance. We can do things more quickly and more economically than anybody else because we have the fuel in the form that we want it. We don't have to do anything to it; we don't have to test it; we don't have to verify it. That provides an enormous saving in time and money.

Note: For Bibliography, See DCNR (S. Anghaie)



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INSPI WAS CHARTERED AND SPONSORED BY SDIO/IST, BEGINNING IN SEPTEMBER, 1985. IT HAS BEEN OPERATING AS A NATIONAL CONSORTIUM OF UNIVERSITIES AND HIGH TECHNOLOGY BUSINESSES PERFORMING MULTI-DISCIPLINARY, MULTI-INSTITUTIONAL RESEARCH ON ADVANCED AND INNOVATIVE NUCLEAR SPACE POWER REACTORS AND ENERGY CONVERSION SYSTEMS. ITS GOVERNMENT CONTRACTS ARE ADMINISTERED BY WPAFB. INSPPI IS AN INSTITUTE OF THE STATE UNIVERSITY SYSTEM OF FLORIDA.

THE INSTITUTIONS AND PROJECTS FROM SEPTEMBER '85 - PRESENT INCLUDED:

MMW GAS CORE REACTORS

- CALIFORNIA STATE UNIVERSITY, LONG BEACH
- UNIVERSITY OF CALIFORNIA, LOS ANGELES
- UNIVERSITY OF FLORIDA, GAINESVILLE
- GA TECHNOLOGIES
- MAXWELL S
- J. DORNING ASSOC. (UNIV. OF VIRGINIA)
- PACIFIC SIERRA RESEARCH CORP.
- AVCO
- RICHARD ROSA, MSU (CONSULTANT)
- LANL
- RTS, INC.
- SPACE POWER, INC.
- SRI, INTERNATIONAL

INDUCTIVE COUPLING THERMIONICS (TRICE)

- RASOR ASSOCIATES
- OREGON GRADUATE RESEARCH CENTER (OSU)
- SPACE POWER, INC.
- THERMOELECTRON

NUCLEO-CHEMICAL CONVERSION

- ANN ARBOR NUCLEAR, INC.
- UNIVERSITY OF MICHIGAN

METAL VAPOR TURBO-ALTERNATOR

- SPACE POWER, INC.
- UNIVERSITY OF NEBRASKA

Figure 1

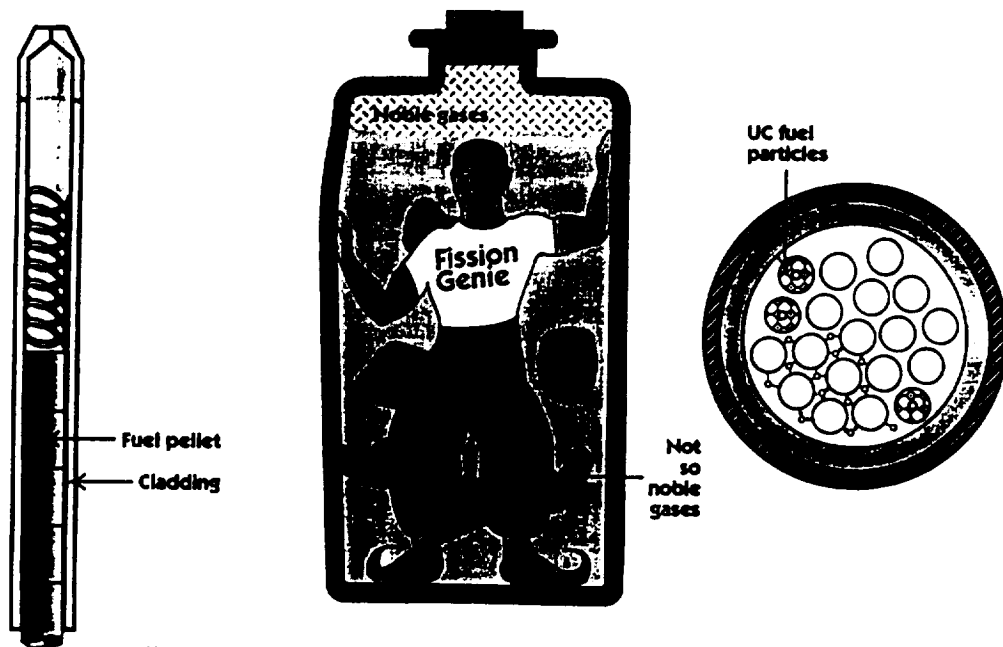


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RECENT VAPOR CORE REACTOR RESEARCH

- INSPI HAS BEEN ADDRESSING THE CRITICAL SCIENCE AND TECHNOLOGY OF VAPOR (GAS) CORE REACTORS SINCE 1985 FOR SDIO.
- MANY CONCEPTS WERE EXAMINED AND A PROGRAM CENTERPIECE CONCEPT (AND ALTERNATE) SELECTED TO FOCUS THE RESEARCH IN OCTOBER 1988.
- A UF_4 /KF VAPOR CORE-MHD SYSTEM IN A CLOSED RANKINE CYCLE IS THE PRIMARY CONCEPT.
- RESEARCH PROGRAM IS NOW FOCUSED ON EXPERIMENTAL VERIFICATION AND MODELING OF SCIENTIFIC FEASIBILITY AND CRITICAL TECHNOLOGY ISSUES.
- SIGNIFICANT RESEARCH ACCOMPLISHMENTS
 - UF_4 IS PREFERRED CHEMICAL FUEL FORM FOR $T < 5000K$,
U-METAL DROPLETS FOR $3000K < T < 7000K$,
U-VAPOR FOR $T > 6000K$
 - W, MO, RE, C AND THEIR ALLOYS & CARBIDES IDENTIFIED AS MATERIALS COMPATIBLE WITH UF_4 ABOVE 1800K
 - NEUTRONIC STABILITY OF EXTERNALLY MODERATED GAS CORE INCREASES AS FUEL DENSITY DISTRIBUTION APPROACHES CAVITY WALL
-- FOR CENTRALLY-PEAKED DISTRIBUTION, $V_{fuel} > 0.85 V_{core}$ FOR STABILITY
 - ENHANCED ELECTRICAL CONDUCTIVITY & MHD ELECTRICAL PRODUCTION CAN BE ACHIEVED VIA DIRECT CHARGED PARTICLE IONIZATION
 - EXPERIMENTAL AND COMPUTATIONAL FACILITIES ESTABLISHED FOR HIGH TEMPERATURE VAPOR CORE NEUTRONICS, FLUID FLOW, HEAT TRANSFER, MHD & MATERIALS ANALYSIS.

Figure 2

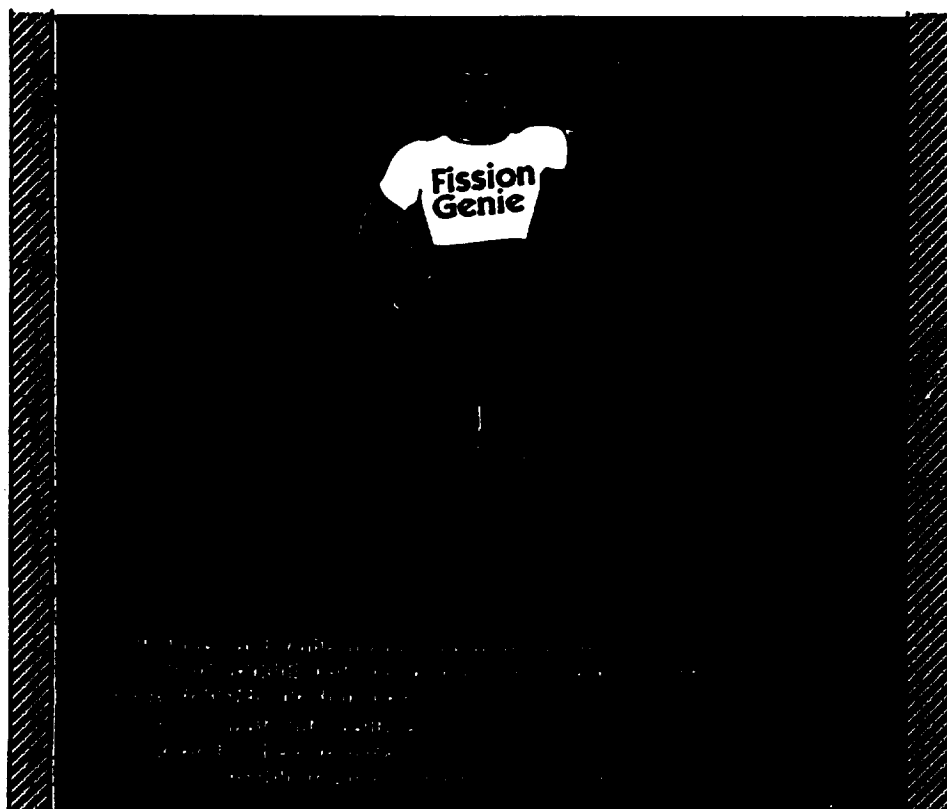


Heat is transferred from and through fuel through cladding and/or coating.
Limits: fuel/cladding temperature, fission/cc³, thermal and mechanical properties, burnup, peaking factors, hot spots, etc.

Solid Reactor Fuel

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Figure 3



ORIGINAL PAGE IS
OF POOR QUALITY

Vapor (Gas) Core Reactors

365

Figure 4

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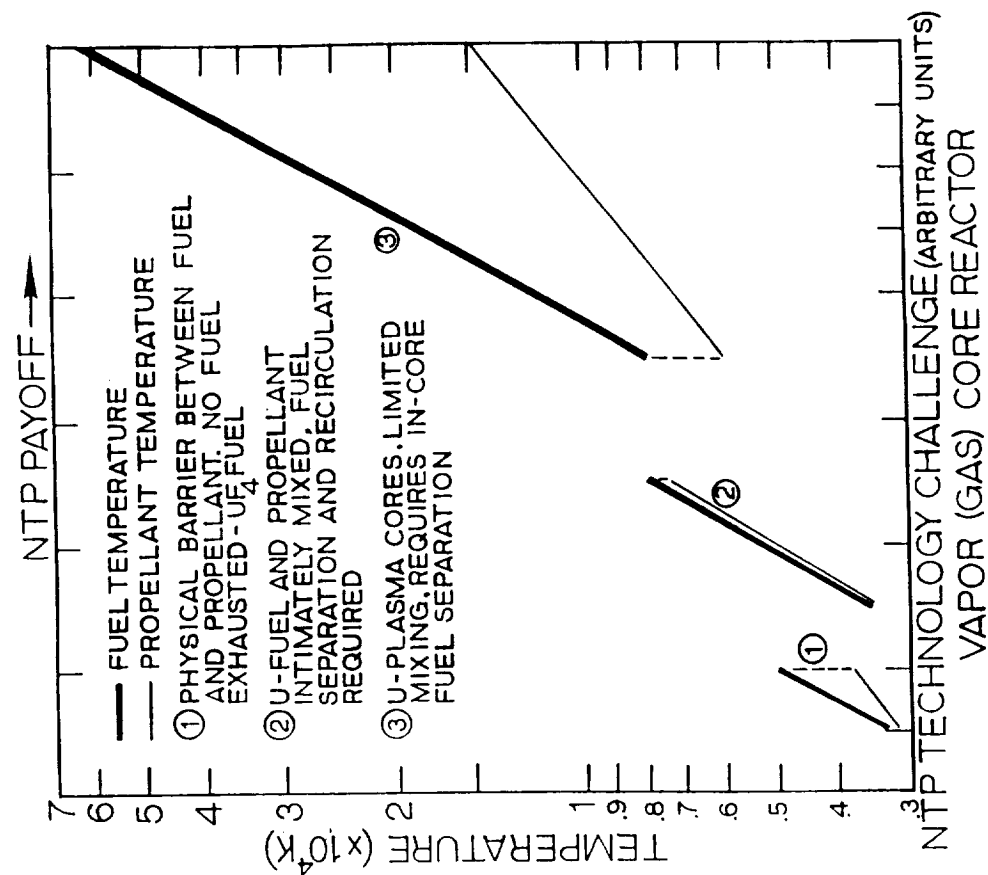
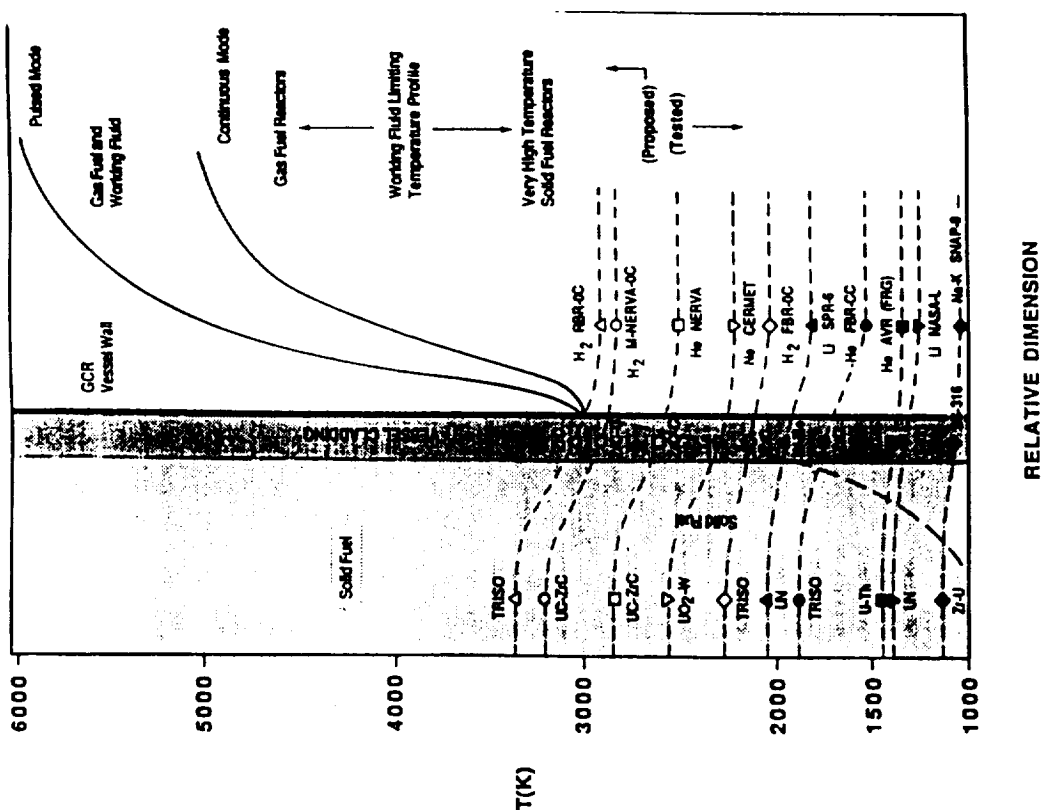


Figure 5



Limiting Temperature Profiles For Solid and Gas-Fuel Reactor

Figure 6

VAPOR (GAS) CORE REACTORS: FUNDAMENTAL FEATURES

- THE NUCLEAR REACTOR AND THE ENERGY CONVERSION SYSTEM ARE NOT LIMITED BY FUEL TEMPERATURE BUT BY WALL-COOLING CAPABILITIES.
- CORE FISSION POWER DENSITY IS NOT LIMITED BY FUEL THERMAL MECHANICAL OR THERMAL HYDRAULIC CONSIDERATIONS.
- THERE ARE NO GEOMETRICAL CONSTRAINTS ON FUEL CONFIGURATION.
- DIRECT IONIZATION (NONEQUILIBRIUM) OF WORKING FLUID CAN IMPROVE THE OPTICAL (LASING) AND ELECTRICAL PROPERTIES OF THE FISSIONING GAS
- THERE ARE THREE ADDITIONAL ENERGY TRANSFER MODES BEYOND THOSE OF SOLID FUEL REACTORS:
 - DIRECT FISSION FRAGMENT ENERGY DEPOSITION
 - DIRECT MOLECULAR COLLISION BETWEEN FUEL AND PROPELLANT
 - RADIATIVE HEAT TRANSFER VIA BLACK BODY AND LINE RADIATION

Figure 7

VAPOR (GAS) CORE REACTOR: DESIGN FEATURES

ADVANTAGES

- HIGH FUEL UTILIZATION (BURNUP ~ 200,000 MWD/MT)
- ELIMINATION OF FUEL FABRICATION, TESTING, VERIFICATION
- SIMPLIFIED FUEL MANAGEMENT
- INHERENT HOT SPOT COMPENSATION; DENSITY DECREASES WITH TEMPERATURE, DECREASING POWER
- FISSION PRODUCT REMOVAL POSSIBLE WITH UF_4 SLIP STREAM (POTENTIAL RADIOISOTOPE RECOVERY)
- INHERENT STABILITY DUE TO EXPANDING FUEL; POWER DISTRIBUTION CAN BE SHAPED BY DENSITY VARIATIONS (NVR)
- FUEL CORE GEOMETRICAL CONSTRAINTS MINIMIZED
- FUEL DENSITY CAN BE VARIED REGIONWISE TO FIT POWER DENSITY AND TEMPERATURE DISTRIBUTION

DISADVANTAGES

- CONFINEMENT, CONTAINMENT, RECIRCULATION OF FUEL
- FUEL RECIRCULATION LOOPS CREATE NEW AND UNIQUE PROBLEMS RANGING FROM EX-CORE CRITICALITY CONSIDERATIONS AND SHIELDING TO MULTIPLE COMPONENT MATERIAL LIMITATIONS.

NUCLEAR VAPOR ROCKET

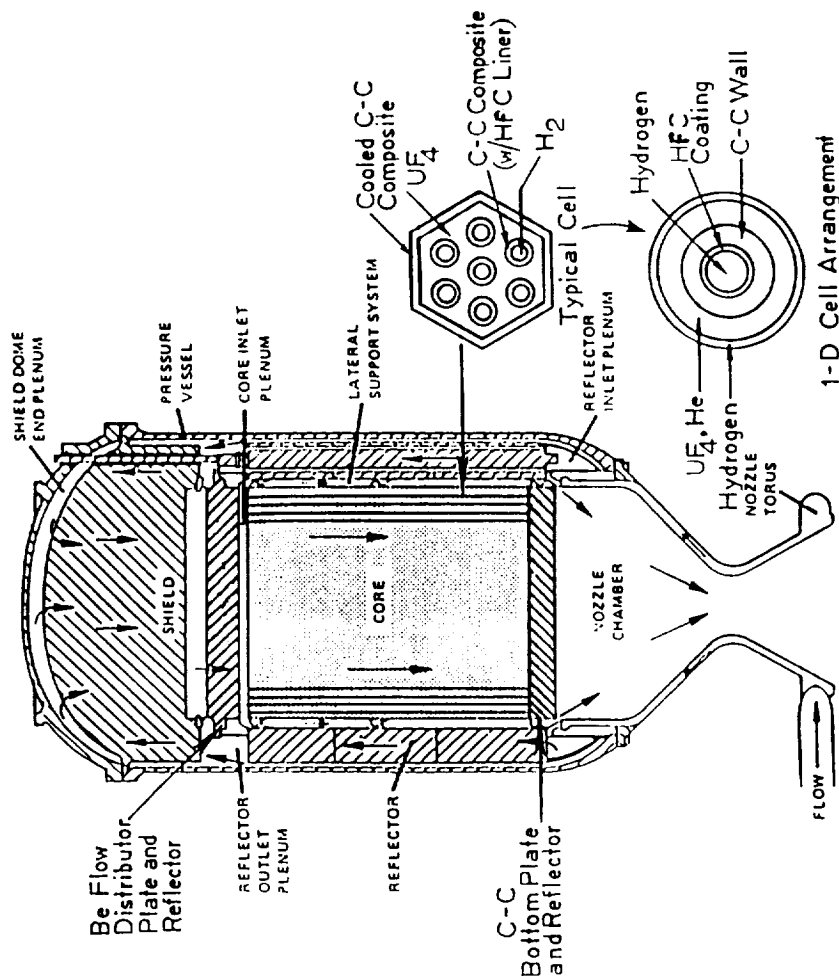


Figure 9

VAPOR CORE REACTORS

BASELINE SYSTEM DESIGN PARAMETERS

REQUIREMENT PARAMETER	UNITS:	NVR	VCVR
ENGINE AVAILABILITY	YEAR	2015	2020
THRUST PER ENGINE	KLB (F)	75	75
NUMBER OF ENGINES	NUMBER	1-7	1
REACTOR POWER (THERMAL)	MW (T)	1250	1650
DUAL MODE-LOW ELECTRIC POWER	KWe	50	25-50
DUAL MODE-HIGH ELECTRIC POWER	MWe	-	1-3
CORE WEIGHT - UNSHIELDED	KLB	33	31
CORE WEIGHT - WITH 0.75M SHIELD	KLB	55	53
ENGINE THRUST/WEIGHT	KLB (F) / KLB (M)	1-2	1-2
SPECIFIC IMPULSE	SECONDS	1280	1810
NOZZLE EXPANSION RATIO	RATIO	50:1	50:1
PROPULSION OPERATING TIME/MISSION	MINUTES	PROPELLANT-LIMITED	PROPELLANT-LIMITED
NUMBER OF MISSIONS	NUMBER	2	1
NUMBER OF STARTUP CYCLES/LIFETIME	NUMBER	12	6
AVERAGE MISSION DURATION	DAYS	310	240
RELIABILITY		?	?

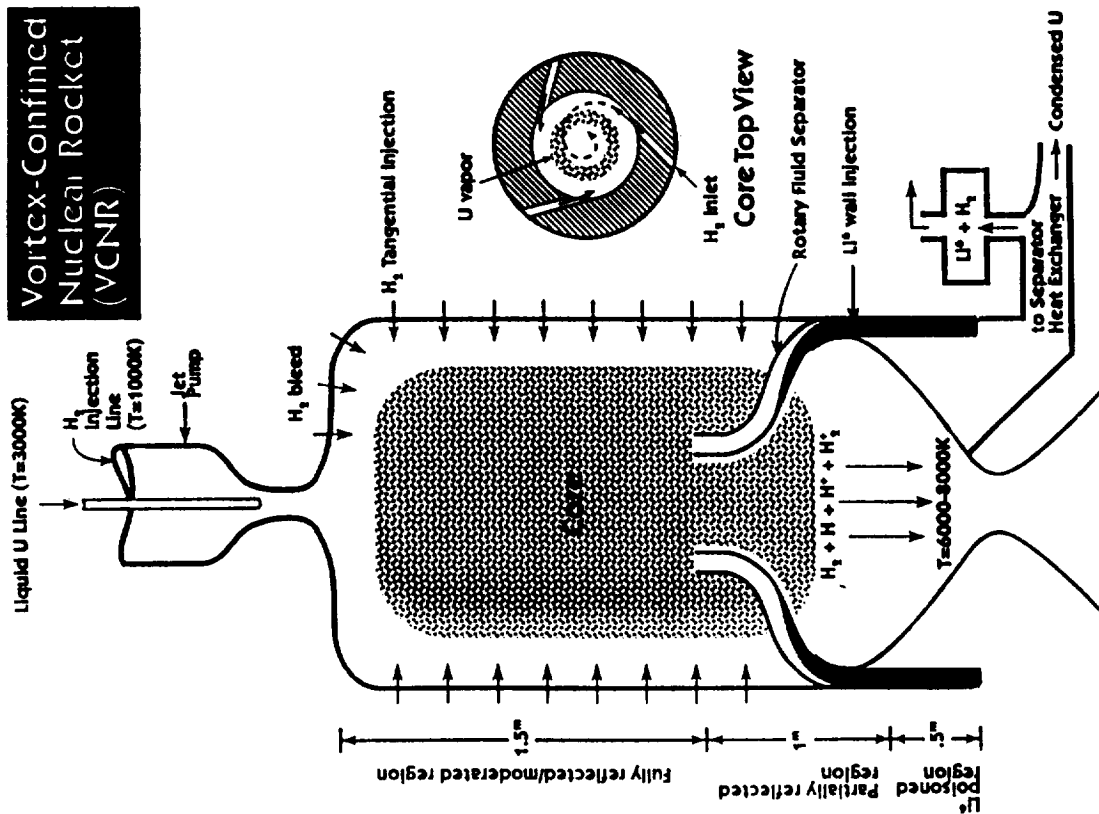


Figure 11

VAPOR CORE PROPULSION REACTORS

SCIENTIFIC/TECHNICAL ISSUE	TECHNOLOGY READINESS LEVEL	
	NVR	VCYR
• CORE CRITICALITY & DYNAMICS	3	2
• CAVITY OR CHAMBER WALL COOLING	3	2-3
• FUEL CONFINEMENT/SEPARATION		
- WITHOUT INTERNAL HEAT GENERATION	-	2
- WITH INTERNAL HEAT GENERATION	-	1
• VAPOR FUEL		
- RECIRCULATION	2*	2
- VAPORIZATION & CONDENSATION	2*	2
• FUEL/WORKING FLUID CHARACTERIZATION	3/4	2-3
• ENERGY TRANSFER AND TRANSPORT	4	2-3
• MATERIALS COMPATIBILITY	2-3	2-3
• THERMAL MANAGEMENT	3-4	2-3

*SLIP STREAM ONLY, FOR REACTOR CONTROL & POTENTIAL RADIOISOTOPE RECOVERY

Figure 12



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REQUIRED TECHNICAL DEVELOPMENT

91-92

- . UF_4 FUELED MINI-CAVITIES
 - TEST AT HIGH TEMPERATURE, NO NEUTRONS
 - TEST AT LOW TEMPERATURE, 10^8 - 10^{12} N/CM² SEC
 - TEST AT FFTF, 1000 K, HI ϕ
 - . τ , Δp VS T , p
 - . DESTRUCTIVE ANALYSIS
- . UTREC FACILITY
 - NOZZLE TEST FACILITY UPGRADE
 - RUN WITH UF_4 - CF_4 -HE

Figure 13



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REQUIRED TECHNICAL DEVELOPMENT (CONT'D)

93-95

LOW POWER (~20-100 KWTH), UF_4 FUELED, FLOWING
CRITICAL FACILITY

- . USE BE (KIWI) AND PLASMA CORE CAVITY (PCC) AT PAJARITO SITE, LANL (SHIELD PCC, RUN @ 20-100 KWTH OR HIGHER, UF_6) @ 500K
- . UPGRADE CAVITY DESIGN, MATERIALS TO $T = 2500\text{K}$, FLOWING UF_4

CRITICAL TEST REQUIREMENTS

- THERMOPHYSICAL PROPERTIES OF UF_4 - CF_4 -He SYSTEM
- UF_4 HANDLING, RECIRCULATION AND FLOW
- MATERIALS INTERACTION/COMPATIBILITY
- REACTOR/REACTIVITY DYNAMICS AND STABILITY VIA FUEL DENSITY FEEDBACK CONTROL
- ACHIEVEMENT OF REQUIRED POWER DENSITY
- CRITICALITY AT POWER, TEMPERATURE CONDITIONS; INTERNALLY MODERATED AND CAVITY REACTOR
- INTEGRAL REACTOR/COOLANT ENGINE TEST

SAFETY ISSUES

- REACTOR TRANSIENT RESPONSE
- OUT-OF-CORE CRITICALITY
- FUEL PLATEOUT (MASS TRANSPORT)
- TUBE RUPTURE ANALYSIS

Figure 15

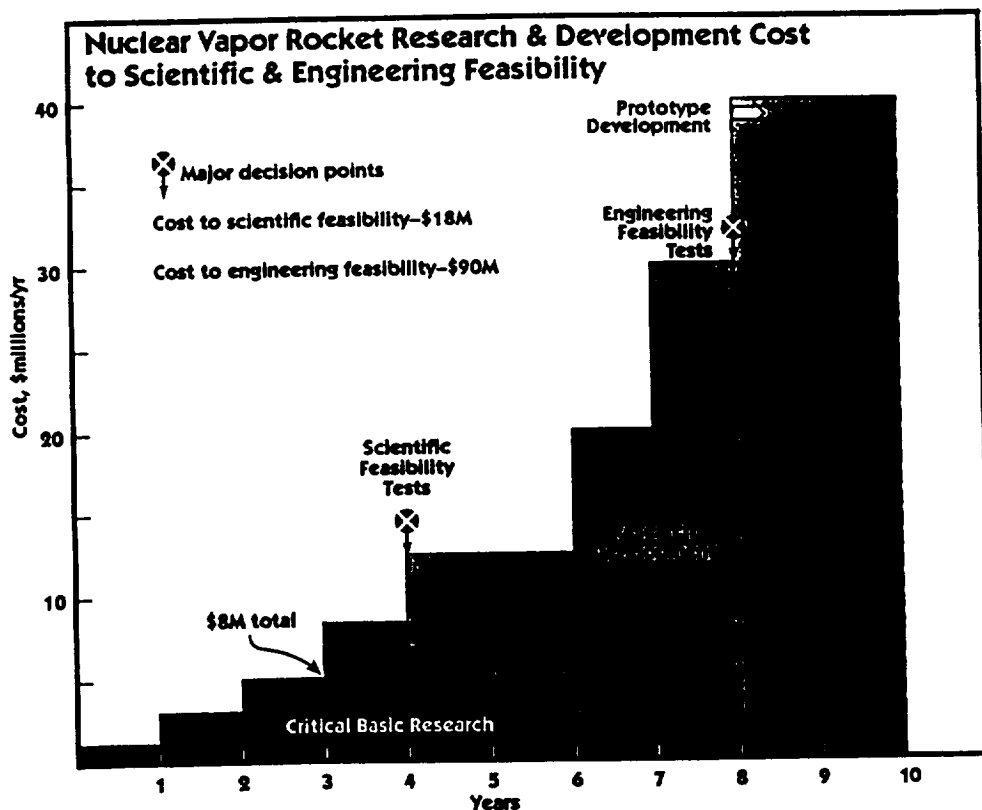


Figure 16

